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Single- and Dual-Band Bandpass Filters Based on a Novel Microstrip Loop-Type Resonator Loaded with Shorted Stubs

Jun-Mei Yan*, Bao-Jie Kang, Yong Yang, and Liangzu Cao

Abstract—A novel microstrip loop-type resonator with four resonant modes is proposed in this letter. The resonator is formed by a loop-type microstrip line loaded with four shorted stubs. It has a symmetrical structure, thus the odd-even-mode method is adopted to implement the resonant analysis. The novelty of the proposed resonator lies in two aspects. One is that its resonant frequencies can be adjusted in a more flexible way. The other is that its resonant modes have a uniform electromagnetic field distribution, which is beneficial for the excitation of resonant modes. For the purpose of demonstration, based on the novel resonator, a single-band bandpass filter with four transmission poles and a dual-band bandpass filter with two transmission poles in each passband are constructed. Additionally, source-load cross coupling is introduced, and several transmission zeros are generated in the stopband, which improves the out-of-band performance greatly. The designed single-band filter has the central frequency of 2.4 GHz and fractional bandwidth (FBW) of 4.5%, and the dual-band filter has the central frequency of 1.8/2.4 GHz and fractional bandwidth of 2.0%/2.5%. The two bandpass filters are designed, fabricated, and measured. Agreement between the simulated and measured results verifies the effectiveness of the proposed resonator and filters.

1. INTRODUCTION

Multi-mode resonators have multiple resonant modes in which resonant frequencies can be independently controlled. Multi-mode resonators can be used to construct many types of microwave components, such as multi-band bandpass filters, diplexers, and power dividers. The microstrip loop-type (or called ring) multi-mode resonators have received extensive interests due to their simple structure, easy fabrication, and low lost. Its first-order degenerate modes can be split through loading a patch [1–3] or a notch [4, 5], to form the single-band bandpass filters. However, these single-band filters had only two transmission poles in the passband. In [6, 7], dual-band bandpass filters were proposed based on a loop-type resonator. In [6], two pairs of split first- and second-order degenerate modes were used to form two passbands. In [7], two pairs of split first- and third-order degenerate modes were used to form two passbands. A triple-band bandpass filter was presented in [8] based on three pairs of split first-, second- and third-order degenerate modes. These multi-band filters had their central frequencies only being controlled in a limited range.

In [9], a loop-type resonator was loaded with shorted/opened stubs. Its three modes can be controlled independently, which were utilized to form a triple-band filter. Thus their central frequencies can be controlled in a wider range. However, its first two modes had quarter-wavelength, and the third mode had half-wavelength, which means an inconsistent electromagnetic field distribution. Additionally, a complicated port coupling structure and an inter-resonator coupling structure make it difficult to design the filter. A dual-band filtering power divider was proposed based on a loop-type resonator loaded with opened stubs in [10]. Indeed, only two modes were used with one mode in each passband,

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* Corresponding author: Jun-Mei Yan (yjmzhy@163.com).
The authors are with the School of Mechanical and Electronic Engineering, Jingdezhen Ceramic University, China.

thus each passband had only one transmission pole. Ref. [11] presented a balanced bandpass filter based on a loop-type resonator loaded with shorted/opened stubs. Two resonant modes formed the passband of the differential-mode signal, and for the common-mode signal, the other two resonant modes also formed a passband. Due to the different central frequencies, the common-mode signals are suppressed in the operational band.

This letter presents a loop-type resonator loaded with all shorted stubs. Its four resonant modes are all half-wavelength long with two ends grounded and can be controlled in a more flexible way, which gives a flexible way to construct the filters and a simple method to excite the resonant modes. Based on the resonator, a dual-band filter with two transmission poles in each passband and a single-band filter with four transmission poles are constructed. The microstrip parallel coupling line is used to excite the resonator. Additionally, direct source-load coupling is introduced to generate transmission zeros to improve the out-of-band performance. In the following sections, the resonant analysis about the resonator is given. The design process about the two filters are detailed. For purpose of verification, the designed filters are fabricated and measured. Although a small discrepancy between the measured results and simulated ones exists, the fabricated filters can verify the effectiveness of the proposed resonator and filters constructed by it.

2. STRUCTURE AND RESONANT ANALYSIS

Figure 1(a) depicts the schematic of the proposed microstrip loop-type resonator loaded with four shorted stubs. The resonator is symmetric, and it has two symmetry axes represented by the dashed lines. Z_0 is the characteristic impedance of the microstrip line. θ_1 and θ_2 are the electric-length of the shorted stubs. The microstrip loop-type resonator has the whole electric-length of $4\theta_3$. Due to the symmetry, odd-even-mode method can be adopted to implement the resonant analysis. The circuits of its four resonant modes are shown in Figures 1(d)–(g), and f_1, f_2, f_3, f_4 are the resonant frequencies corresponding to Modes 1–4.

The four resonant modes all have electric-length of half-wavelength and have their two ends grounded. Thus, they all have an uniform electromagnetic field distribution just as depicted in Figure 2(a). Figure 2(b) and Figure 2(c) depict the electric-field distributions of other two microstrip resonant modes just as in [1, 10]. Figure 2(b) also has the electric-length of half-wavelength, but its two ends are opened. Thus, it has a different electromagnetic field distribution compared with Figure 2(a). However, they have the same resonant frequencies if they have the same length. They can also be called

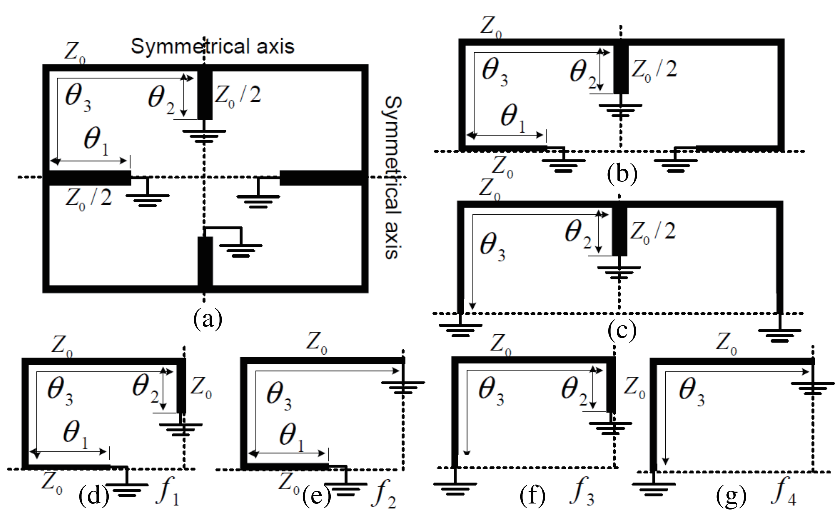


Figure 1. The proposed microstrip loop-type resonator (a) and its resonant modes: even-mode (b) and odd-mode (c) bisection and further even-even-mode (d), even-odd-mode (e), odd-even-mode (f), odd-odd-mode (g).

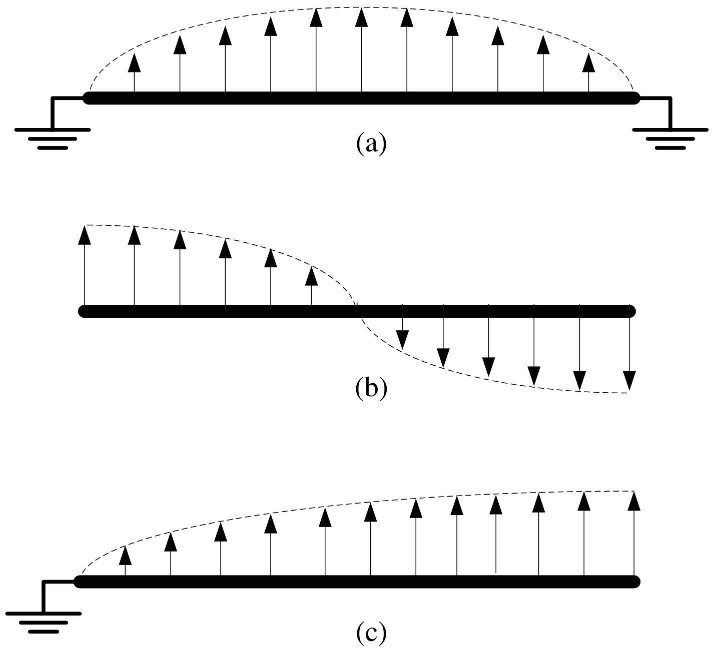


Figure 2. Electric-field distribution of three different microstrip resonant modes: two ends shorted (a), two ends opened (b) and one end shorted and other opened.

degenerate modes. Just as mentioned in Section 1, the degenerate modes are split through loading a patch [1–3] or a notch [4, 5] to form the single-band bandpass filters. Figure 2(c) has the electric-length of quarter-wavelength with one end shorted and the other opened. Its resonant frequency is half of modes in Figure 2(a) or Figure 2(b) if they have the same length. Thus, it is difficult to adjust the resonant frequency of Figure 2(c) close to one of Figure 2(a) or Figure 2(b) when modes in Figure 2 are used simultaneously.

Resonant frequencies of the four resonant modes in Figure 1 can be obtained from the following formulas,

$$f_1 = \frac{\pi}{\theta_1+\theta_2+\theta_3}\cdot f_0, \quad f_2 = \frac{\pi}{\theta_1+\theta_3}\cdot f_0, \tag{1}$$

$$f_3 = \frac{\pi}{\theta_2+\theta_3}\cdot f_0, \quad f_4 = \frac{\pi}{\theta_3}\cdot f_0 \tag{2}$$

According to Eqs. (1) and (2), the resonant frequencies can be determined. Without lost generality, the reference frequency f_0 of all electric-length is assumed to be 2.4 GHz and $\theta_3 = \pi$. Figure 3 gives the resonant frequencies against various values of θ_1, θ_2. It can be observed that resonant frequencies f_2,

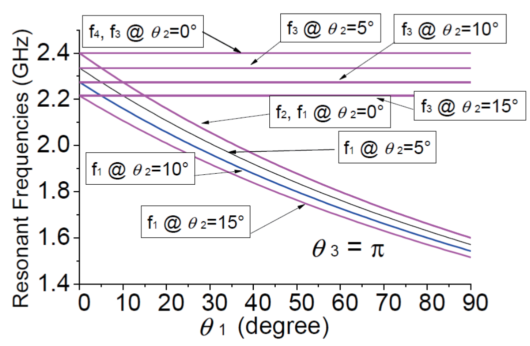


Figure 3. The resonant frequencies against values of θ_1, θ_2.

f_4 are not related to θ_2, and the distance between f_2 and f_4 can be adjusted by changing θ_1. Resonant frequency f_1 is equal to f_2, and resonant frequency f_3 is equal to f_4 when θ_2 is zero. Changing value of θ_2 will change f_1 and f_3 simultaneously. From above analysis, it can be concluded that a single-band filter with four transmission poles or a dual-band filter with two transmission poles in each passband can be easily constructed based on the loop-type resonator if choosing a proper port coupling structure.

3. CONSTRUCT AND DESIGN OF THE BANDPASS FILTERS

Figure 4(a) gives layout of the bandpass filter based on the proposed loop-type resonator. The microstrip parallel coupling line (L_4) with one end shorted is used as the port coupling structure. It can not only excite the four resonant modes, but also introduce direct source-load coupling through gap S_2. The coupling topology is also given in Figure 4(b). The coupling strength can be adjusted by changing length (L_4) and gap width (S_2) of the microstrip parallel coupling line. The external quality factors can be extracted according to the following formula [12],

$$Q = \frac{\omega_0 \tau}{4} \tag{3}$$

In (3), ω_0 is the resonant angular frequency, and τ is the group delay at ω_0.

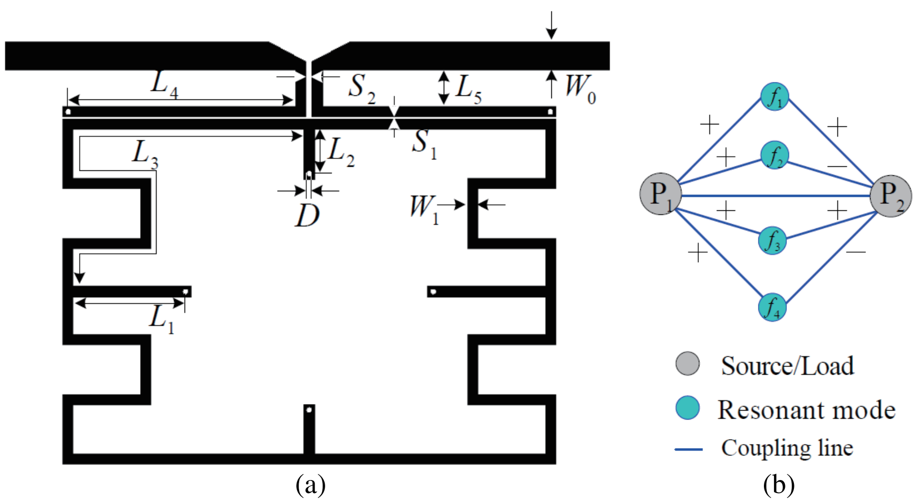


Figure 4. Layout of the bandpass filter based on the proposed microstrip loop-type resonator (a) and its coupling scheme (b).

3.1. Single-Band Bandpass Filter

A single-band bandpass filter with a central frequency of 2.4 GHz and FBW of 4.5% ($S_{11} < 20$ dB) is designed. The used microstrip substrate is F4B-2, which has relative permittivity of 2.55 and thickness of 0.8 mm. HFSS 15.0 is used as the field simulation tool. The passband range is from 2.454 GHz to 2.346 GHz. The four modes all resonate in the passband. Mode 4 has the highest resonant frequency; here, its resonant frequency can be roughly set as 2.46 GHz, thus L_3 can be determined. Mode 1 has the lowest resonant frequency; here, its resonant frequency can be roughly set as 2.34 GHz, thus, the sum of $L_2 + L_3$ can be determined. Resonant frequencies of Modes 2 and 3 can be set between 2.34 GHz and 2.46 GHz with different values of L_2 and L_3 but with the sum of L_2 and L_3 unchanged. Then, the quality factors are extracted. Figure 5(a) gives the extracted quality factors against various L_4. It can be observed that the four modes have almost the same quality factors. From Figure 5, the length L_4 can be obtained. Lastly, a whole simulation is taken, and tuning steps are needed. The final simulated results are given in Figure 5(b). The central frequency of the passband is at 2.4 GHz, and its FBW is 4.8%. The specified filtering response is obtained. Four transmission zeros can be observed out of the passband, which are generated by the direct source-load coupling introduced by gap S_2.

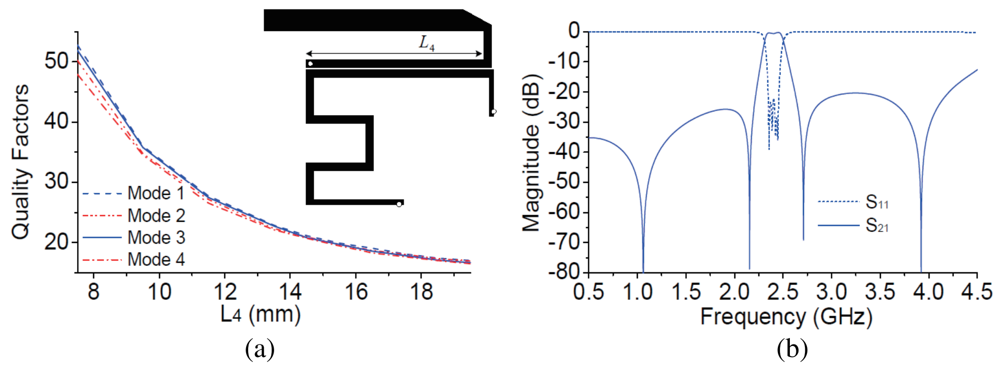


Figure 5. The extracted quality factors against various L_4 (a) and the final simulated results (b) of the single-band passband filter. The final dimensions (units mm): $L_1 = 0.95$, $L_2 = 0.18$, $L_3 = 43.1$, $L_4 = 18.75$, $L_5 = 3.0$, $W_0 = 2.2$, $W_1 = 0.8$, $S_1 = 0.2$, $S_2 = 0.5$, $D = 0.5$.

3.2. Dual-Band Bandpass Filter

A dual-band bandpass filter with central frequency of 1.8/2.4 GHz and FBW of 2.0/2.5% is designed. The first passband range is from 1.782 GHz to 1.818 GHz. The second passband range is from 2.37 GHz to 2.43 GHz. Modes 1 and 2 resonate in the first passband. Modes 3 and 4 resonate in the second passband. Mode 4 has the highest resonant frequency; here, its resonant frequency can be roughly set as 2.44 GHz, thus L_3 can be determined. Then, the resonant frequency of mode 2 can be roughly set as 1.82 GHz through adjusting L_1. Adjusting L_2 will change the resonant frequencies of modes 1 and 3 simultaneously, thus, only one mode, i.e., mode 1 or mode 3 can be freely designed by adjusting L_2. Now the resonant frequency of mode 1 can be roughly set as 1.78 GHz, or the resonant frequency of mode 3 can be roughly set as 2.37 GHz. Then the quality factors are extracted. Figure 6(a) gives the extracted quality factors against various L_4. It can be observed that modes 1 and 2 have almost the same quality factors, and modes 3 and 4 have almost the same quality factors. From Figure 6(a), the length L_4 can be obtained. Lastly, a whole simulation is taken, and tuning steps are needed. The final simulated results are given in Figure 6(b). The central frequencies of the two passbands are 1.8/2.4 GHz, and their FBWs are 2.1/2.6%. The specified filtering response is obtained. Six transmission zeros can be observed out of the passband, which are generated by the direct source-load coupling introduced by gap S_2.

From above discussion, a rough design process can be concluded as follows. Firstly, the desired mode resonant frequencies can be obtained based on the specified central frequency and FBW. Secondly, based

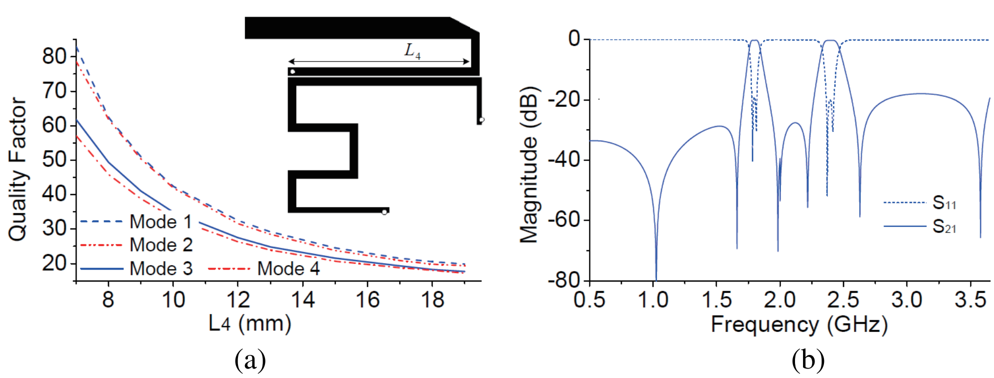
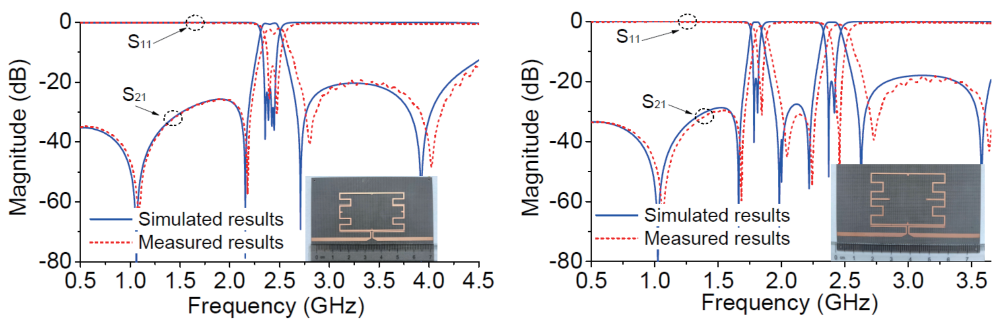


Figure 6. The extracted quality factors against various L_4 (a) and the final simulated results (b) of the dual-band passband filter.. The final dimensions (units mm): $L_1 = 9.05$, $L_2 = 0.53$, $L_3 = 43.7$, $L_4 = 18.3$, $L_5 = 3.0$, $W_0 = 2.2$, $W_1 = 0.8$, $S_1 = 0.2$, $S_2 = 0.5$, $D = 0.5$.

on the resonant frequencies, sizes of the loop-type resonator (L_1, L_2, L_3) can be determined. Thirdly, choose proper length (L_4) and gap width (S_2) of the microstrip parallel coupling line to realize the proper port coupling. Lastly, a whole simulation is taken to realize the desired filtering response.

4. MEASUREMENT RESULTS AND DISCUSS

For the purpose of verification, the designed filters are fabricated. The vector network analyzer (Agilent E5071B) is used for measurement. The circuit size of single-band filter is $29.6 \times 40.6\,\text{mm}^2$, about $0.34 \times 0.47\lambda_g^2$, where λ_g is the guided wavelength of the 50-Ohm microstrip line at the center frequency. The circuit size of dual-band filter is $33.8 \times 39.6\,\text{mm}^2$, about $0.39 \times 0.46\lambda_g^2$, where λ_g is the guided wavelength of the 50-Ohm microstrip line at the center frequency of the upper passband. Two bandpass filters have almost the same sizes. From Figure 7(a), it can be observed that the fabricated single-band filter has its center frequency shifted to 2.44 GHz. It has the return loss of 14.4 dB, and the corresponding FBW with $S_{11} < 14.4$ dB is 4.7%. The insertion loss is 3.8 dB. Four transmission zeros at 1.08/2.18/2.80/4.03 GHz can be clearly observed although small deviations exist. From Figure 7(b), it can be observed that the fabricated dual-band filter has its center frequencies shifted to 1.84/2.45 GHz. The corresponding FBW with $S_{11} < 20$ dB is 1.5/2.2%. The insertion loss is 1.6/1.3 dB. Six transmission zeros at 1.06/1.68/2.05/2.24/2.73/3.64 GHz can be clearly observed although small deviations exist. The shifted center frequencies and transmission zeros may be due to the inhomogeneous permittivity of the substrate. The large insertion loss is due to the large tangent loss of the used microstrip substrate of F4B-2. Additionally, the fabrication errors will also deteriorate the performances. Table 1 gives a comparison with other similar works. It can be observed that the proposed loop-type resonator has a more flexible way to construct the filters. Additionally, It can introduce more transmission zeroes in the stopband, thus, having better out-of-band performances.



(a) (b)

Figure 7. The measured and simulated results: (a) the single-band filter and its photograph as inset, (b) the dual-band filter and its photograph as inset.

Table 1. Comparison with other similar works.

Refs.	f_0 (GHz)	IL (dB)	Num. of TPs		Num. of TZs
			Single-band	Dual-band	
(1)	1.1	1.0	2	/	2
(4)	1.59	3.1	2	/	2
(6)	2.4/5.8	1.4/3.2	/	2.2	4
(7)	2.38/4.87	2.0/1.4	/	2.2	4
(10)	3.1/5.3	3.9/4.0	/	1.1	2
This work	2.44 1.84/2.45	3.8 1.6/1.3	4	2.2	4 6

TPs: Transmission Poles TZs: Transmission Zeroes

5. CONCLUSIONS

A novel microstrip loop-type resonator loaded with shorted stubs is proposed. It has four resonant modes, and their resonant frequencies can be adjusted in a large range. Additionally, all the four resonant modes have uniform electromagnetic field distributions. Thus the proposed resonator has a more flexible way to construct the bandpass filters. For the purpose of demonstration, based on the novel resonator, a single-band bandpass filter with four transmission poles and a dual-band bandpass filter with two transmission poles in each passband are constructed. The resonant analysis of the proposed resonator and the design method of the single- and dual-band filter are detailed. The bandpass filters are fabricated and measured. The simulated and measured results are given. Although a small discrepancy between the measured and simulated results exists, the fabricated filters can verify effectiveness of the proposed novel resonator and corresponding bandpass filters based on it.

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